Shadow Geometric Analysis Utilising CityGML Models and FME

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Abstract

This research presents a methodology for conducting shadow geometric analysis, specifically the shadow boundary in an urban model. Input data include a georeferenced CityGML LoD2 and terrain model. Additional land cover data is used to exclude some parts of the model from analysis. Shadow computation is based on a sunray vector, which is computed based on the sun position on the given day and time. The geometry of original models are divided into parts classified as either exposed to the sun or shaded. It can be used for analytical purposes in other applications, such as urban planning, energy assessment, and photovoltaic potentiality analysis, by accurately identifying sunlit and shaded areas within 3D city models. The analysis is performed in the FME software package, which is a general-purpose ETL tool.

1. Introduction

Extreme weather conditions affect our daily lives. Heat waves are more frequent, posing significant challenges to health and quality of life. Cities are particularly affected by these conditions due to the urban heat island effect. Detecting and mitigating excessive solar exposure is important in urban planning, where shadow analysis plays a crucial role (Alam et al., 2013). This analytical approach is also useful for assessing the solar potential of building surfaces. For instance, tree planting can mitigate excessive solar radiation on buildings, contributing to urban thermal comfort and energy efficiency (Leduc et al., 2021).

Shadow analysis methods are fundamental in computer graphics. Realistic visualisation of city models is essential in applications such as urban planning, navigation, decision making, etc. The core engine usually includes 3D geometric building models accompanied by other city objects. This can be improved by providing a high level of details or textures applied to facades, but also by visualisation of shadows cast by buildings and other objects at a specific location, date and time (Biljecki et al., 2017).

Graphical engines used for visualisation, such as CesiumJS, are based on 3D scene construction where fast algorithms generate shadows projected onto objects (Buyukdemircioglu and Kocaman, 2020). A high level of realism is achieved, but only from the observer’s point of view. Invisible surfaces or those covered by other objects are not rendered and included in the shadow computation. This approach is well justified in the context of fast visualisation of large models, but not for analytical applications where shadow geometry is required.

Another group of applications, where shadows, or rather the amount of sunlight, are important is irradiance analysis (Willenborg et al., 2018; Xu et al., 2024). It is used for calculating PV potential and selecting of the best location of panels on roofs or on land. Spatial models are usually represented as a 2.5D mesh consisting of regular cells (Lukač et al., 2024). Irradiance is computed for each mesh cell based on the cell location, sun position, and sunlight occlusion. This method also does not provide precise shadow boundaries.

Some methods based on geometric analysis focus on the percentage of shadowed surfaces in relation to the total area (Lilis et al., 2017; Luo et al., 2020). Others, implemented in various software packages, are usually black boxes, which are designed to perform specific analysis, without the possibility of deriving the exact shadow shape to be used for purposes other than those anticipated.

The majority of methods are ray-based techniques, particularly ray tracing. Shadowed areas are determined by casting rays from a surface point toward the light source and checking for occlusions. This is computationally heavy and requires efficient algorithms, especially when several light sources are used, transparent and semi-transparent objects are present in a scenes and soft shadow edges are considered (Kolivand and Sunar, 2013; Woo et al., 1990). However, when a single light source is used, e.g. the sun, and only areas exposed to the sun or in shadow need identification, the algorithms are much simpler, often relying on projection algorithms or visibility tests to determine if a surface point is obstructed from direct solar radiation (Vo and Laefer, 2019). Contrary to ray-tracing methods, AI-based techniques are applied to perform rapid shadow analysis (Omar et al., 2025).

Various libraries and software tools are available for conducting solar potential estimation and shadow casting (Dorman et al., 2019). They are designed for specific applications, which makes it difficult or impossible to derive the precise geometry of shadows, which could be used for broader urban planning or environmental analyses in general purpose data processing software, such as FME[1]. It is a platform for spatial ETL operations supporting several formats, including CityGML, ESRI shapefile, various raster and vector formats, as well as non-spatial data, e.g. CSV, text and many others.

The paper presents a method for calculating a shadow geometry cast by 3D buildings on other buildings and terrain for a specific

[1] https://fme.safe.com/

sun position at a specific date and time. As a result, original geometries are divided into set of polygonal faces where each face is classified as either exposed to the sun or shaded. Analysis is performed in FME using standard transformers and integrated Python code.

2. Methods

The computation process was divided into two parts: model preparation and shadow calculation. All the computation was performed in FME Form 2025. Two separate workbenches were developed reflecting these two parts: the first focuses on preprocessing of a 3D CityGML model and terrain model, while the second executes the shadow computation to determine sunlit and shaded regions.

2.1 Model preparation

This preparation phase is important for the subsequent shadow casting computations, which can be performed for a series of timestamps using the same spatial model. Thus, it is not necessary to recompute the model for each timestamp, significantly improving computational efficiency for time-series analyses.

Three input datasets representing the following features are used in the model preparation: terrain, buildings and water bodies. Terrain in the Geo-TIFF format is converted to the surface model, triangulated irregular network (TIN), using the TINGenerator transformer. It is overlaid with water bodies represented as polygons using the Clipper transformer. The same overlay operation is performed for building footprints, which are derived from the CityGML LoD2 model. The area occupied by water and buildings is excluded from shadow analysis. Then the terrain surface model is saved in a single file in the FME Feature Store (FFS) format, where features are classified as: building footprint, water body and remaining terrain. It will be used as an input dataset in the shadow analysis. Buildings with selected attributes, e.g. gml_id are also stored as 3D solids in an FFS file.

Another parameter required in the second part is a sunray vector, which is essential for shadow cast computation. An algorithm for an approximate solar position proposed by Michalsky (1988) was implemented in Python and integrated into the PythonCaller transformer. It requires the following input parameters: longitude, latitude, date, and time of day. The first two parameters are computed based on a centre point (CenterPointReplacer transformer) of a bounding box (BoundingBoxAccumulator transformer), calculated for the building model. The date and time are provided by a user as an input parameter in a *yyyyMMddHHmm* format, where yyyy – year; MM – month; dd – day; HH – hour in the 24h format; mm – minutes. It should be noted that the daylight saving time is automatically calculated for the CET/CEST zone as the analysis was performed only for locations in Poland. The sunray vector (x, y, z) is used as an input parameter for the second workbench.

In a case where the last four digits of a datetime string, i.e. *HHmm*, are ‘0000’, then a list of sunray vectors for a certain time is generated in time intervals, e.g. every one hour. The list is limited to the time period between sunrise and sunset at the specific location. The second workbench is run individually for each item on the list, while building and terrain models stay the same.

A simplified flowchart presenting the first FME workbench is shown in Figure 1.

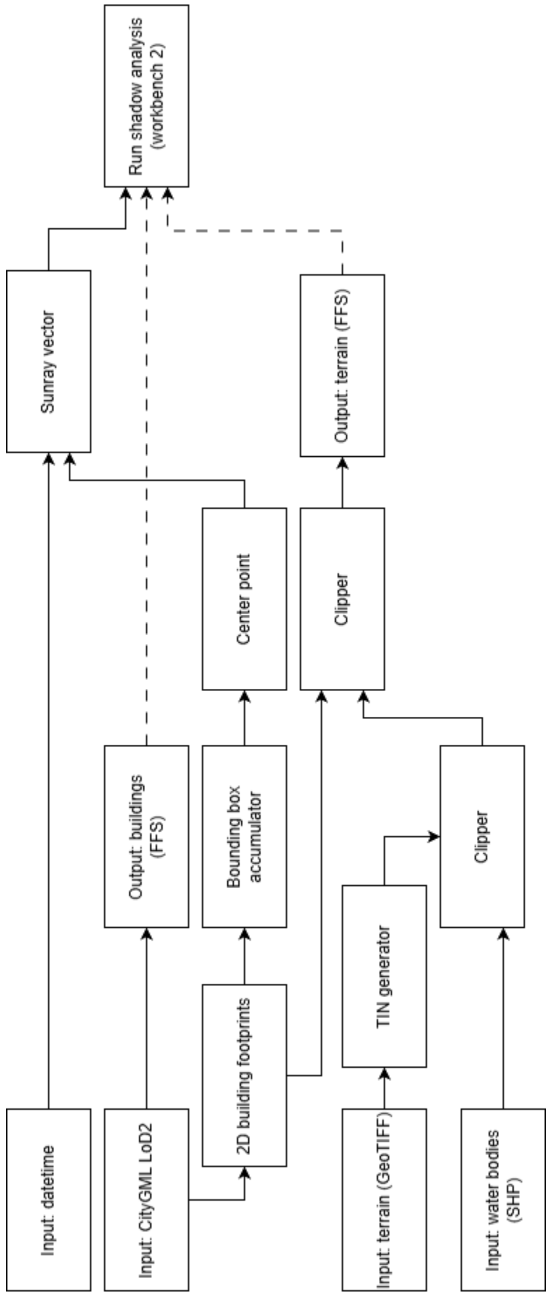

Figure 1. Model preparation flowchart.

2.2 Shadow calculation

Shadow calculation is split into three processes: shadow cast by a building on the terrain, shadow cast by a building on other buildings, and shadow cast by a building on itself. Shadow cast by the terrain on buildings was not taken into consideration as relatively flat terrain was investigated in this research. Also, no trees nor other city objects were included in analysis.

The first step is the same for all the processes – building features, originally represented as 3D solids, are split into individual faces. A combination of the Deaggregator and GeometryCoercer transformers is applied. Faces have a group attribute attached – gml_id of the building they belong to. A normal vector for faces is calculated. A dot product of two vectors, the normal vector and sunray vector, allows for identification of faces, which are exposed to the sun and shadowed. This filter is implemented in the PythonCaller transformer limiting the number of faces used in further analysis. It is assumed that only the faces of a closed solid, whose normal vector forms an angle of less than 90° with the sun vector, i.e. faces exposed to the sun, are essential in shadow cast calculation, and the shadowed faces are ignored. Only the faces exposed to the sun are extruded according to the direction of the sunray vector using the Extruder transformer. This extrusion represents a shadow volume – everything inside is shaded.

3D extrusions of individual faces are used in the process of a shadow cast by a building on itself. The Clipper transformer is used to overlap the shadow volume with original building’s faces. After this operation, it is essential to check if a face is not inside the shadow volume created by the same face – such relationship should be excluded from results.

When a shadow cast by a building on other buildings and the terrain is computed, all shadow volumes created from faces of a certain building (faces with the same gml_id) are merged using the SolidDissolver transformer. Results generated by the Clipper transformer should be filtered to avoid situation when a shadow volume created for a certain building is overlaid with the faces of the same building – only parts of faces inside of the shadow volume belonging to other buildings are considered shaded. In the same way the Clipper transformer is applied to cast building shadows on the terrain.

The shadow calculation process shown in Figure 2 is included in the second FME workbench.

3. Results

The case study covers the area of the Kleczków district in Wroclaw, Poland. An urban digital twin (UDT) was developed in the DigiTwin4PEDs[2] project, in which energy consumption simulations are performed and various tools are designed and implemented to support energy flexibilization in positive energy districts. The district area is almost 1.9 km^2. It is a diversified part of the city with residential, commercial, and industrial areas. There are 431 buildings included in the UDT stored in the CityGML 2.0 format (Zielonka et al., 2026). Open datasets: terrain model in the GeoTiff format and land cover, specifically water bodies in the ESRI Shapefile format, were obtained from the Polish national geoportal[3].

The study area was limited to a bounding box defined by the UDT, with a centre point at latitude 51.1299, longitude 17.0306. All datasets were spatially filtered and adjusted to cover the same area. They were reprojected to the same coordinate system, namely EPSG:2180. This coordinate system, is a Polish national realization of the European Terrestrial Reference System 1989, providing high precision for geospatial analyses within the region.

The terrain was converted to TIN. The original raster 2,979 x 1,210 pixels (see Figure 3a) was processed by the TINGenerator transformer (Surface Tolerance parameter = 1). The resulting mesh consisted of 39,838 triangles. Building footprints and polygons representing water bodies (mostly the Odra River) were overlaid onto the terrain model and subsequently removed from further analysis (see Figure 3b). The difference between the highest and lowest terrain point is less than 16 m, with the lowest points located at the river.

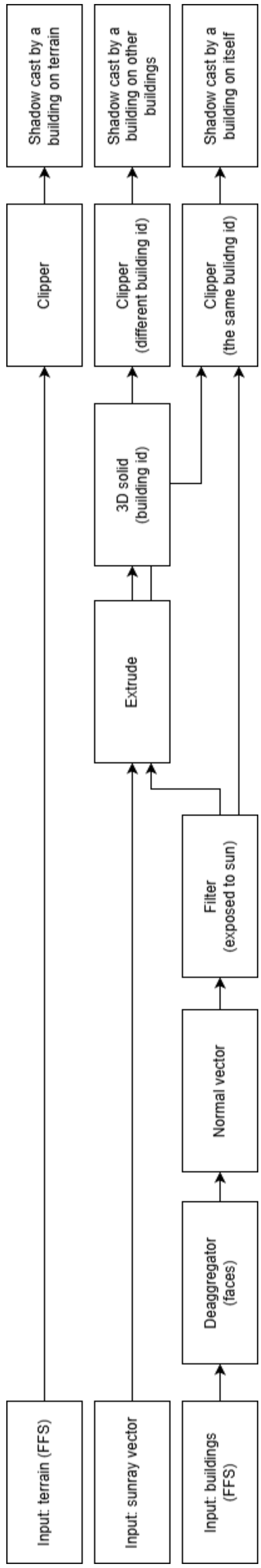

Figure 2. Shadow calculation flowchart.

[2] https://digitwins4peds.eu

[3] https://mapy.geoportal.gov.pl/

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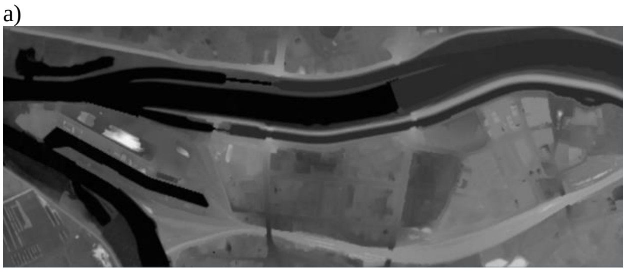
a)



b)

Figure 3. Terrain model of the Kleczków district: a) original raster; b) TIN model with excluded buildings and water bodies.

Shadow analysis was performed for the hottest day in 2025, 15/08/2025, with the highest temperature 31.9°C[4], which is much above the average. According to the Institute of Meteorology and Water Management in Poland[5], the average maximum temperature measured between 1991 and 2020 is 25.4°C.

The shadow analysis was executed for 13 discrete sunray vectors at one-hour intervals from 7:00 am to 7:00 pm. The sun was above the horizon during this period. The vector’s values are presented in Table 1, and its visual representation in Figure 4.

It should be noted that the sunray vector for each specific time was calculated at the central point of the bounding box, which spans less than 3 km between its extreme points. Sunray vectors computed for these extreme locations do not differ significantly from the central vector. Thus, it was applied to all buildings.

Table 1. Sunray vectors on 15/08/2025 from 7:00 am to 7:00 pm.

x	y	z	Time
-0.9703	-0.1395	-0.1975	7:00
-0.9333	0.0558	-0.3547	8:00
-0.8327	0.2370	-0.5004	9:00
-0.6753	0.3917	-0.6249	10:00
-0.4719	0.5095	-0.7195	11:00
-0.2362	0.5823	-0.7779	12:00
0.0155	0.6051	-0.7960	13:00
0.2663	0.5764	-0.7726	14:00
0.4989	0.4981	-0.7092	15:00
0.6975	0.3756	-0.6102	16:00
0.8486	0.2173	-0.4823	17:00
0.9419	0.0339	-0.3342	18:00
0.9710	-0.1621	-0.1760	19:00

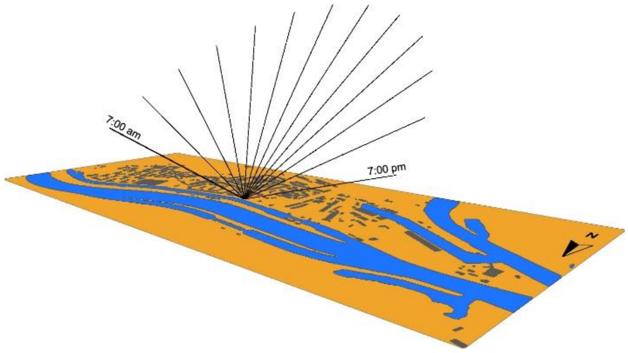
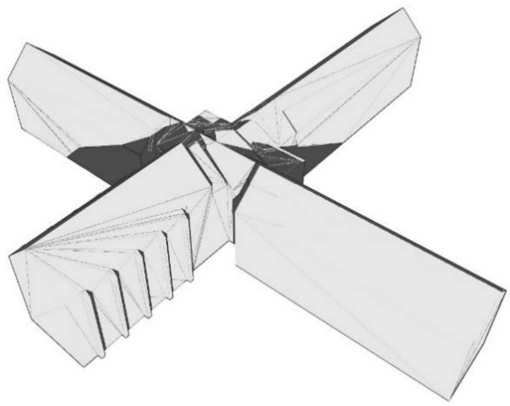


Figure 4. Sunray vectors on 15/08/2025 from 7:00 am to 7:00 pm.

Buildings, originally stored as 431 3D solids, were divided into 7,352 faces. Based on the dot product of the normal vector determined for each face and the sunray vector, the faces exposed to the sun were selected. For instance, 3,855 faces were exposed at 7:00 am and 3,877 at 7:00 pm. Only these faces were extruded and used in further computation, which significantly reduced the number of processed entities. Another optimisation involved computing the shadow cast on a building by itself, reducing it to faces belonging to that building. One of the complex buildings with many small faces and protrusions is shown in Figure 5a. The same object, with shadows cast by surrounding buildings, is shown in Figure 5b.

a)



b)

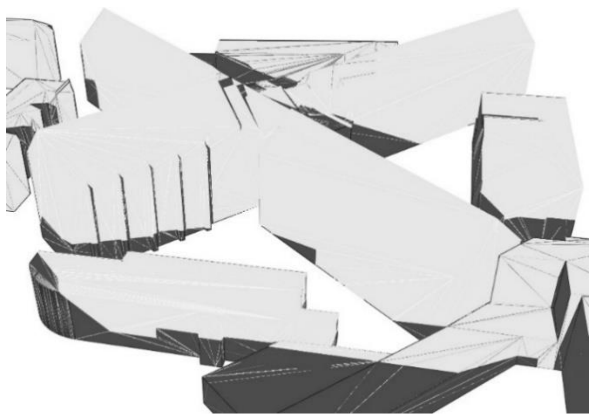


Figure 5. A building with shadows cast by a) itself, and b) other buildings, on 15/08/2025 at 8:00 am.

[4] Temperature data obtained from Open-Meteo (open-meteo.com)

[5] https://imgw.pl/

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The result of shadow analysis is a set of classified faces, where the class determines whether a face is exposed to the sun or it is in shadow. Consequently, it was possible to calculate a ratio for all the buildings in the district, representing the proportion of sunny and shaded areas (see Table 2). Only roof and wall faces were taken into consideration as floor faces are never exposed to the sun.

Table 2. Ratio between building faces exposed to the sun and those in shadow on 25/08/2025 from 7:00 am to 7:00 pm.

Ratio	Time
0.661792208	07:00
0.891223229	08:00
1.024045033	09:00
1.139265334	10:00
1.197487461	11:00
1.196326834	12:00
1.246277236	13:00
1.223123663	14:00
1.206896144	15:00
1.147628399	16:00
1.044105865	17:00
0.900660572	18:00
0.656739624	19:00

The results of the above analysis were used to identify potential locations of heat islands. The shadow cast on the terrain was calculated in order to identify areas exposed to direct sunlight. The time range from 12:00 pm to 6:00 pm was taken into consideration, as during this time the temperature exceeded 30°C. The terrain exposed to direct sunlight during the hottest period of the day is shown in Figure 6. Water bodies, building footprints, and shadow cast by buildings were overlayed with the terrain model and removed.

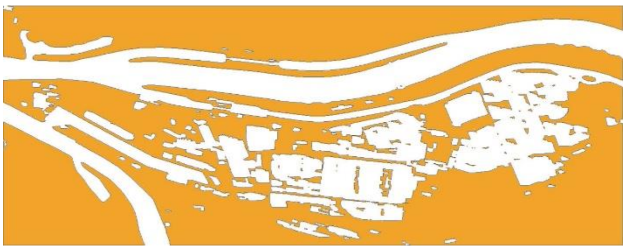

Figure 6. Area with no shadow (orange) on 15/08/2025 between 12:00 pm and 6:00 pm.

In order to confirm the accuracy of the presented method it was compared to shadow analysis available in Cesium[6]. It is a core 3D visualisation engine in the internet platform developed in the DigiTwins4PEDs project. Because the same building model was used in the project and this research, a comparison was straightforward. Figure 7 shows a part of the model with shadows at exactly the same time, 6:00 pm. The shadow boundary is similar in both cases. It is not possible to compare them using spatial analysis as no geometric details are available in the case of Cesium, where shadows are calculated from the perspective of an observer only for rendering purposes.

a)

b)

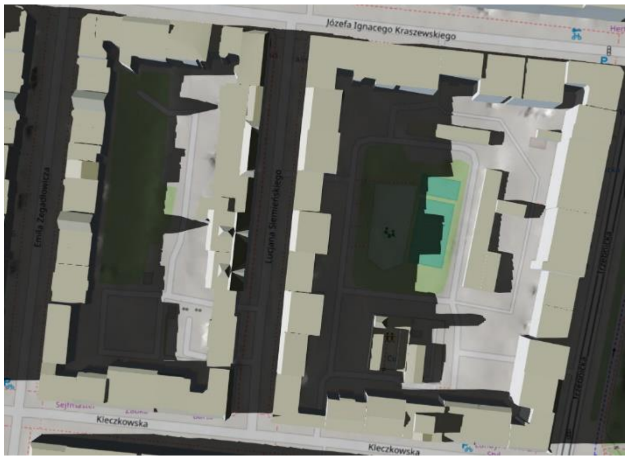

Figure 7. Comparison of results: a) shadow analysis in FME; b) shadow analysis in CesiumJS.

The model preparation and shadow analysis for the 13 sunray vectors took 49.5 minutes in total. The computations were performed on a computer equipped with an Intel Core i9 processor (3.5 GHz) and 32 GB of RAM.

4. Conclusions

In this paper, a method for geometric shadow analysis is proposed. A CityGML building model, terrain model, and sunray vector, calculated for a given date and time, are used to compute areas exposed to the sun and in shadow. Detailed geometric results can be used in an analytical approach, such as heat island analysis.

A CityGML LoD2 model, consisting of 431 buildings developed in the DigiTwins4PEDs project, was used. Terrain model and land cover data were obtained from open repositories available in the national geoportal.

Trees and other city objects were not considered in this research due to the lack of appropriate models at the time of computation. Such objects may be included in the computation process in the same way as buildings. However, vegetation may require a different approach considering the transparency of leaves, which do not block light as other solid objects, and can produce soft shadows.

[6] https://cesium.com

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The method did not include the shadow cast by the terrain. The case study analysed in this research is relatively flat, without steep forms such as hills. In mountainous areas, it is necessary to take this into consideration.

The proposed method may be extended to deal with more detailed models including buildings with windows and indoor spaces. This could be used in practical applications to calculate how much sunlight enters indoor spaces. This could be potentially useful information for individuals purchasing a property.

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